Application of a 2D Hydraulic Model to Reach-scale Spawning Gravel Rehabilitation

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Abstract

In-channel features such as woody debris, hydraulic jumps, and gravel bars are ubiquitous in natural rivers. An increasing body of research has detailed their geomorphic and ecologic importance for aquatic habitat. Existing rehabilitation practice minimizes or even ignores the impact of these features and instead focuses on channel geometry via stream classification. Few objective criteria exist for designing in-channel features. In this study we tested the applicability of a 2D hydraulic model for use in gravel placement to restore salmon spawning habitat and natural fluvial complexity.

The Mokelumne River is a major stream of California's Central Valley whose salmonid production is limited by low spawning habitat quality and quantity. Habitats are degraded by minimal gravel recruitment due to river impoundment and historic gravel extraction. In Fall 1999, 3,200 cubic yards of gravel, woody debris and boulders were used to create bars and chutes in a 300 ft reach below Camanche Dam.

A 2D hydraulic model was used to simulate sub- and super-critical flows within the project reach. A low and a high discharge, 330 and 1,100 cfs, were modeled for pre- and post-project conditions. Model runs were calibrated to match observed water surface elevations, discharges, bed roughness and eddy viscosities. Post-project runs were validated with observed depth and velocity profiles.

After the project, water surface slope and velocities increased, while depths decreased. The gravel replenishment dramatically increased the coefficient of variation of depth and enhanced that of velocity. Such changes mark an important step in habitat rehabilitation. Low flow runs produced model features that match observed dry banks, islands, and boulders. Using Shields' criteria and the log-velocity profile, sediment entrainment was assessed and found to be negligible. Overall, the 2D model is a useful tool for assessing, and ultimately designing, rehabilitation projects when used in conjunction with existing geomorphic methods.

INTRODUCTION

In-channel features such as large woody debris, hydraulic jumps, and alluvial bars are ubiquitous in natural rivers. An increasing body of research has detailed their geomorphic and ecologic importance for aquatic habitat (Hawkins et al., 1993). Existing river restoration practice minimizes or even ignores the impact of these features and instead focuses on channel geometry via stream classification. Few objective criteria exist for designing and placing in-channel features.

One such in-channel feature that has been significantly degraded by river management has been gravel bars (Sear, 1995). Gravel bars are required for the successful spawning of salmon, as eggs are deposited in clusters (egg pockets) and buried in nests (redds) in the gravels. Man-made reservoirs obstruct natural gravel replenishment from upstream, thereby degrading and ultimately destroying downstream gravel stream beds. Artificial replenishment of gravels downstream of a reservoir has the potential to mitigate the anthropogenic impact depending on the design and implementation of a replenishment strategy (Kondolf, 1997). In order to design a replenishment program that will successfully restore and maintain instream physical habitats, it is necessary to understand the physical processes of gravel entrainment, transport, and deposition, because these processes determine the response of natural systems to the restoration effort.

This report summarizes the current status of the collaborative University of California, Davis (UC Davis) and the East Bay Municipal Utility District (EBMUD) section of the federally-funded Mokelumne River Gravel Enhancement Project (FWS Agreement #113328J200).

OBJECTIVES

The overall goal of this study was to test the applicability of a 2D depth-integrated hydraulic model for use in optimizing fine-scale gravel placement in streams to restore salmon spawning habitat and natural fluvial complexity. The site where the model was tested is a gravel placement project on the Mokelumne River downstream of Camanche Reservoir. As the model was developed after the 1999 gravel placement, there was limited opportunity to collect pre-project data. Consequently, the model provides an initial characterization of the hydraulics of pre- and post- project conditions, with several lessons for future application in placement design and implementation. Specific objectives of the project have been to:

- Construct a 2D model that estimates the spatial distribution of stable and unstable bed configurations in an alluvial channel reach subjected to gravel replenishment.
- Calibrate and validate the model using observed field data to assess the ability of the model to match real conditions.
- Compare and contrast the pre- and post-gravel replenishment hydraulic and geomorphic conditions.

Use the hydrodynamic model to identify gravel distributions that minimize spawning gravel losses and secondarily maximize in-stream physical habitat as identified by fishery biologists.

STUDY SITE

The Mokelumne River is a major stream in the Central Valley of northern California whose salmonid production is limited by low spawning habitat quality and quantity. The river and its floodplain have had a long history of regulated flow, water diversion, gravel extraction, levee construction, and land development. Studies of river impacts have concluded that aquatic habitats are primarily degraded by 1) minimal gravel recruitment due to river impoundment by 16 dams and 2) historic gravel extraction, such as that which took place downstream of Camanche Dam, where sand and gravel were taken for construction aggregate and gold prospecting (Kondolf, 1997).

Three species of anadromous fishes occur at the study site: fall-run chinook salmon (*Oncorhynchus tshawytscha*), steelhead trout (*Oncorhynchus mykiss*), and Pacific lamprey (*Lampetra tridentata*). Due to their value as a sport and commercial fishery, chinook salmon are considered the primary focus in management of the lower Mokelumne River (CDFG 1991). The majority of salmon spawning now takes place in the 9-mile reach between Camanche Dam and Elliott Road. For the 34-year post-impoundment period, chinook salmon runs averaged approximately 3,300 spawners.

In 1990, EBMUD initiated an experimental spawning gravel project by placing about 500 cubic yards of suitable sized gravel in the lower Mokelumne River just below Camanche Dam. The goal was to enhance existing spawning areas as a means of increasing reproductive success of anadromous fishes. The project has been continued over subsequent years in cooperation with California Departments of Fish and Game, Parks and Recreation and U.S. Fish and Wildlife Service. In 1991, fall-run Chinook escapement from the tributary was 410 fish. From 1990 to 1997, 3,550 cubic yards of gravel were placed in the river. Overall, escapement increased to 10,163 over that period, but it is not possible to directly attribute this change to the gravel projects (J. Merz, pers. comm.).

In Fall 1999, 3,200 cubic yards of gravel, woody debris and boulders were added to a 300 ft reach below Camanche Dam (Figure 1). Historical salmon spawning stock surveys conducted by the DFG indicated that the most spawning occurred upstream of Mackville Road (CDFG 1991). Before gravel replenishment, this site was typical of a faster riffle-run habitat. The project sediment was used to form channel features including longitudinal bars, transverse bars, and chutes (Figure 2).

METHODS

A combination of field data collection and computer modeling were required to meet the study's objectives. While detailed field data and geomorphic analyses are necessary for river rehabilitation, this project is focused on the applicability of 2D models. Consequently, the only field data collected was that required to calibrate and validate the model. Future studies will need to determine how such models should be integrated into broad-based geomorphic assessment.

Field Data Collection

Three types of field measurements are required to calibrate and validate the 2D hydraulic model. The first of these is the bathymetry of the river channel, including channel cross-sections and detailed 3D characterization of placed gravel bars. Surveys of the study reach were made before and after gravel placement by EBUMD. In addition to obtaining {x,y,z} coordinates, wet/dry channel boundaries, water surface elevations, and the extent of exposed features in the channel were noted in the surveys (Figure 3). Such information is crucial for the model developer in simulating real field conditions.

The second type of data required is water depth at each discharge to be modeled. Water depth was measured at points across each of 4 cross-sections using standard surveying rods.

The final data required is water velocity. Depth-average velocity was measured at points across each of 4 cross-sections using propeller-type velocity meters and ultrasonic velocity meters either by wading or by boat depending on flow conditions.

Substrate Size

Pebble counts were conducted by EBMUD in 1999 before and after gravel replenishment. Using grain size frequency analysis, it was determined that pre-gravel conditions had a median grain diameter of 40 mm, or 0.13 ft. Post-gravel conditions had a median grain diameter of 50 mm, or 0.18 ft (Figure 4).

2D Hydraulic Model

Initially, the 2D hydraulic model that was going to be used was the U.S. Army Corps. of Engineers RMA2 model. The RMA2 model is based on widely accepted fluid mechanics principles for rivers and shallow estuaries. At its core the model uses depth-integrated 2D statements of mass and momentum conservation that include expressions for temporal and advective inertia, gravity and pressure, and bed and water surface resistance. Turbulence closure is provided by recasting Reynolds stresses in term of an eddy diffusion equation (Shrestha et al., 1997).

As it turned out, the RMA2 model was suitable for pre-project conditions, when river flow is entirely sub-critical, but was not suitable for post-project conditions. The first problem encountered using RMA2 for post-project scenarios was the presence of super-critical flow, which the model is not intended to handle. The second problem was computational instability when the model attempted to determine whether placed bars or even some steep banks were wet or dry. These problems lead to switching from the RMA2 model to the more suitable FEWSMS-2DH model.

The Finite Element Surface Water Modeling System Two-Dimensional Flow in a Horizontal Plane model (FESWMS-2DH v. 2) simulates both steady and unsteady two-dimensional surface-water flow (Froehlich, 1989). FESWMS was developed by the

Federal Highway Administration to analyze flow at bridge crossings where complicated hydraulic conditions occur. This model is suitable for both sub- and super-critical flows. FESWMS numerically solves the vertically integrated equations of motion and continuity, using the finite element method of analysis, to obtain flow depths and depth-averaged velocities. Velocity in the vertical direction is assumed to be negligible, so pressure in a column of water is considered to be hydrostatic.

FESWMS allows mesh elements that are not completely submerged to exist in the finite element network. An element is "dry" if it is connected to at least one node point that is dry. If the minimum water-surface elevation is greater than the maximum ground-surface elevation, plus a small depth tolerance, the element is "wet." Depth tolerance (0.4 ft for this study) is required for model stability.

FESWMS was implemented via the Boss International Surface water Modeling System (SMS). SMS includes a pre-processing module for transforming XYZ boundary data into a finite element mesh. Boundary data primarily consists of channel cross-sections and parameters describing bed material, such as grain size distributions. Cross-sections and some bed material data were be provided by EBMUD. Remaining bed material parameters were measured in the field using methods discussed below. Additional boundary data consist of specified input discharges and associated end-of-reach water depths. Input discharges were obtained from the dam upstream of the study site. Associated depths were measured in the field or obtained from EBMUD.

Model Inputs:

- Bottom boundary: XYZ bathymetry, roughness coefficient
- Upstream boundary: constant outflow from Camanche Reservoir
- Downstream boundary: constant water surface elevatio
- Turbulence closure: constant eddy viscosity

Model Outputs:

Direct model output is provided in the form of 2D color contour plots of 3 hydraulic variables: *water surface elevation, water depth,* and *water velocity*. In addition, SMS allows calculation of additional variables using the direct output.

Froude number (a measure of the inertial effectiveness of the flow) was calculated as

$$Fr = U\ (gD)^{0.5}$$

where U = velocity, g = gravitational constant, D = water depth

To assess whether placed gravels would wash away during the studied flows, critical velocities, U_{crit}, were calculated according to incipient motion criteria.

$$U_{crit} = [(0.045(\gamma_s - \gamma_f)(d_{50})(6.25+5.75\log(D/d_{50}))^2)/\rho_f]^{1/2}$$

Where γ_s, γ_f = specific weights of sediment and fluid, d_{50} = median grain size, D = water depth, ρ_f = fluid density

Sediment Mobility Index (MI) is the ratio of actual velocities predicted by the model to critical velocities. If the mobility index is greater than 1, transport is predicted at that point. If the mobility index is less than 1, no transport is predicted.

$$MI = U_{actual}/U_{crit}$$

Mesh Generation: Meshes were generated using the Map and Mesh modules of the Surface-water Modeling System (SMS) (Figures 5,6). Imported bathymetric data were used to interpolate XYZ data to every node.

Calibration: Water surface slope was used to calibrate the model. Field-determined roughness values and eddy viscosities were applied and held constant over all model runs. Manning's n was determined for a straight, coarse gravel channel with no vegetation as estimated based on roughness tables. Eddy viscosity was estimated as 0.6 D u*, with depth (D) determined from field data and shear velocity (u*) from velocity data coupled with the log-velocity profile.

Scenario	Surface Elevation (ft)	Outflow (cfs)	Manning's n	Eddy Viscosity (ft2/s)
High Pre	93.5	1,100	0.043	0.7
High Post	93.5	1,100	0.043	0.7
Low Pre	92	330	0.043	0.7
Low Post	92	330	0.043	5

Table 1. Calibration parameters for model runs. For low post scenario, eddy viscosity values smaller than 5 ft^2/s led to model instability.

Validation: Post-gravel model runs were validated with depth and velocity profiles taken at high and low flows. Two cross-sections were taken for each flow. Model depths were higher than observed in the field at all cross-sections. At high flows, predicted right bank velocities were higher than observed velocities (Figure 7). This is because the mesh interpolation did not include large woody debris (LWD) along the right bank thrusting into the flow upstream of the cross-sections. In the field, this LWD was observed to block flow along the right bank and produce a slow-water section below and divert faster flow toward the channel center. Cross-section 7 profiles emphasize the need for detailed surveys around enhanced gravel features (Figure 8). Topographic data outlining the features in all directions produce more accurate interpolation results. The model run is missing an island feature in the middle of the cross-section due to model limitations with wetting and drying, averaging out velocities near the right bank. This can be solved by eliminating exposed bars from the mesh prior to simulation runs.

RESULTS

High Flow

Water surface slope increased from pre-gravel (0.0005) to post-gravel (0.0014) scenarios. Added gravel removed pool features between cross-sections 1 and 10, replacing them with bars and chutes (Figure 9). Flows increased throughout the enhanced reach and were redirected from the center of the channel to produce higher velocities near the left bank (Figure 10). Though velocities increased in the enhanced reach, they did not exceed estimated critical velocities necessary for transport of added gravel. According to Froude number calculations, post-gravel flows approached critical values in the study reach (Figure 11). Using Shields' criteria and the log-velocity profile, sediment entrainment for this homogeneous bed was only predicted to occur at the location of super-critical flow over the concrete berm below cross-section 1 (Figure 12).

Low Flow

Water surface slope increased from pre-gravel (0.0002) to post-gravel (0.0017) scenarios. Pre-gravel, more bank elements dried out, while gravel addition produced dry "islands" in the study reach and flooded bank elements that previously were dry (Figure 13). Upstream of the concrete berm, after gravel was added to enhance the bar feature, a pool was created. Thus, flows upstream of cross-section 1 were decreased (Figure 14). Also, the pool downstream of cross-section 10 was deepened from chute flows in the enhanced section. Flows diverge around dry elements. Froude number calculations again show flows reaching critical values in the study reach, with most critical flows occurring in chutes created from gravel replenishment (Figure 15). As in high flow conditions, though velocities increased in the enhanced reach, they did not reach estimated critical velocities necessary for transport of added gravel (Figure 16).

Flow Field Distributions

Depth and velocity distribution statistics were calculated using model output from all nodes from pre- and post- project meshes. Overall, the gravel replenishment project dramatically increased the coefficient of variation (CV) of the depth distribution, and significantly enhanced that of the velocity distribution for the high discharge scenario. Such changes are widely recognized as an important step in habitat restoration.
For high flow (Figure 17):

- Mean depth decreased from pre-gravel (5.3') to post-gravel conditions (4.5'), and the distribution changed from normal to bi-modal.
- Mean velocity increased from pre-gravel (1.9 ft/s) to post-gravel conditions (2.6 ft/s), and the range of velocities increased.
- Depth distribution CV increased by a factor of 254, while that for velocity did not change.

For low flow (Figure 18):

- Mean depth decreased from pre-gravel (3.8’) to post-gravel conditions (3.2’), and the distribution changed from normal to bi-modal.
- Mean velocity increased from pre-gravel (0.8 ft/s) to post-gravel conditions (1.2 ft/s), and the range doubled.
- CVs for depth and velocity distributions increased by 31 and 23 %, respectively.

DISCUSSION

Predicted dry areas from model runs matched generally with observed dry areas. However, mesh size put a limit on mesh refinement, capping element sizes at approximately 5' x 5' quadrilaterals. The wetting and drying algorithm forces elements dry if any connecting node is dry. This produces large areas that can only be either "off" or "on." Shrinking mesh boundaries to enclose only the gravel enhanced reach will allow further mesh refinement, making 1' x 1' (or smaller) elements possible. Eddy viscosity for the low flow post-gravel scenario may then also be lowered to match observed values.

Accurate interpolation depends on detailed bathymetric data. Survey data should detail geomorphic features besides gravel bedforms such as large woody debris in the channel. Large woody debris may provide a significant portion of in-stream habitat and can strongly affect channel hydraulics.

CONCLUSIONS

- 2D hydraulic models can accurately simulate observed in-stream features such as large eddies, boulders and gravel bars. These features impact reach-scale dynamics, scales relevant to ecological habitat parameters
- Gravel replenishment decreased flow depths, increased flow velocities, and increased the coefficient of variation of both depth and velocity through the study reach. These changes significantly enhance the range of available habitats.
- The ultimate success of this gravel replenishment project depends on the stability of the placed gravels. No bed mobility is predicted for any of the four scenarios.

FUTURE WORK

One of the on-going activities with the modeling effort is the improvement of the resolution of 2D flow within the project reach to achieve better accuracy. As it turned out, tributary flows from Murphy Creek are minimal at the modeled Mokelumne River flows, so the area of interest may be confined to the project reach itself. The advantage of reducing the model area stems from the limited number of nodes that may be used in the FESWMS model. As area decreases, more smaller elements may be utilized.

A second on-going activity is a switch in modeling practice. Instead of letting the wet/dry algorithm determine dry areas in the mesh dynamically, we are determining them a priori based on field observations. Under the low flow scenario, placed gravel bars are exposed. By determining the shape and extent of exposed areas prior to simulating a flow, it is possible to achieve more accurate estimates of flow conditions in the vicinity of the bars. Dry areas are being determined from field maps, photos, and digital video of observed flow patterns and exposed features.

The last model improvement planned for the existing project is a change in the handling of bank conditions. Presently, banks are treated the same as the channel bed. In future runs, bank elements will be assigned a second material type, with roughness values and eddy viscosities specific to bank and riparian effects. One reason why this is necessary is that trees, tree roots, and large woody debris are present along the banks, and these features dramatically reduce flow velocity. Such effects should be accounted for in the model.

Beyond improving the model, future work will continue to examine the applicability of commercially available 2D hydraulic modeling software to salmonid habitat management projects. Specific targets include efforts to address:

- the spatial distribution of physical habitat for fish
- the application of current geomorphic theory on various in-channel features and their impacts on salmonid habitat to create alternative placement scenarios
- approaches to incorporating 2D models into broad-based geomorphic assessment.

As EBMUD continues its gravel replenishment in the Mokelumne River, model-generated predictive scenarios should prove beneficial for future management decisions.

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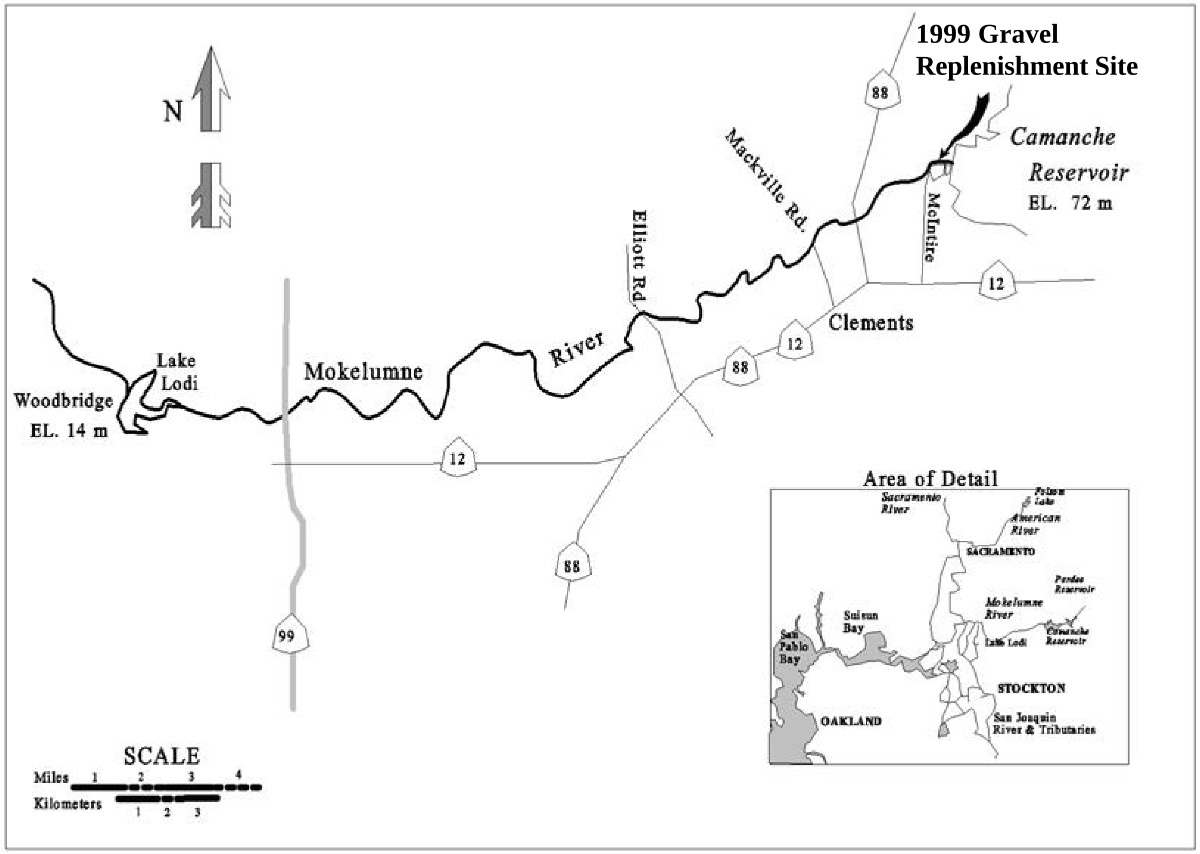


Figure 1. Detail of Camanche Dam area showing 1999 gravel replenishment site.

A)

B)

Figure 2. A) Mid-project channel. B) Post-project channel showing gravel bed features installed as part of habitat replenishment.(Boulder in A shown at far left in B).

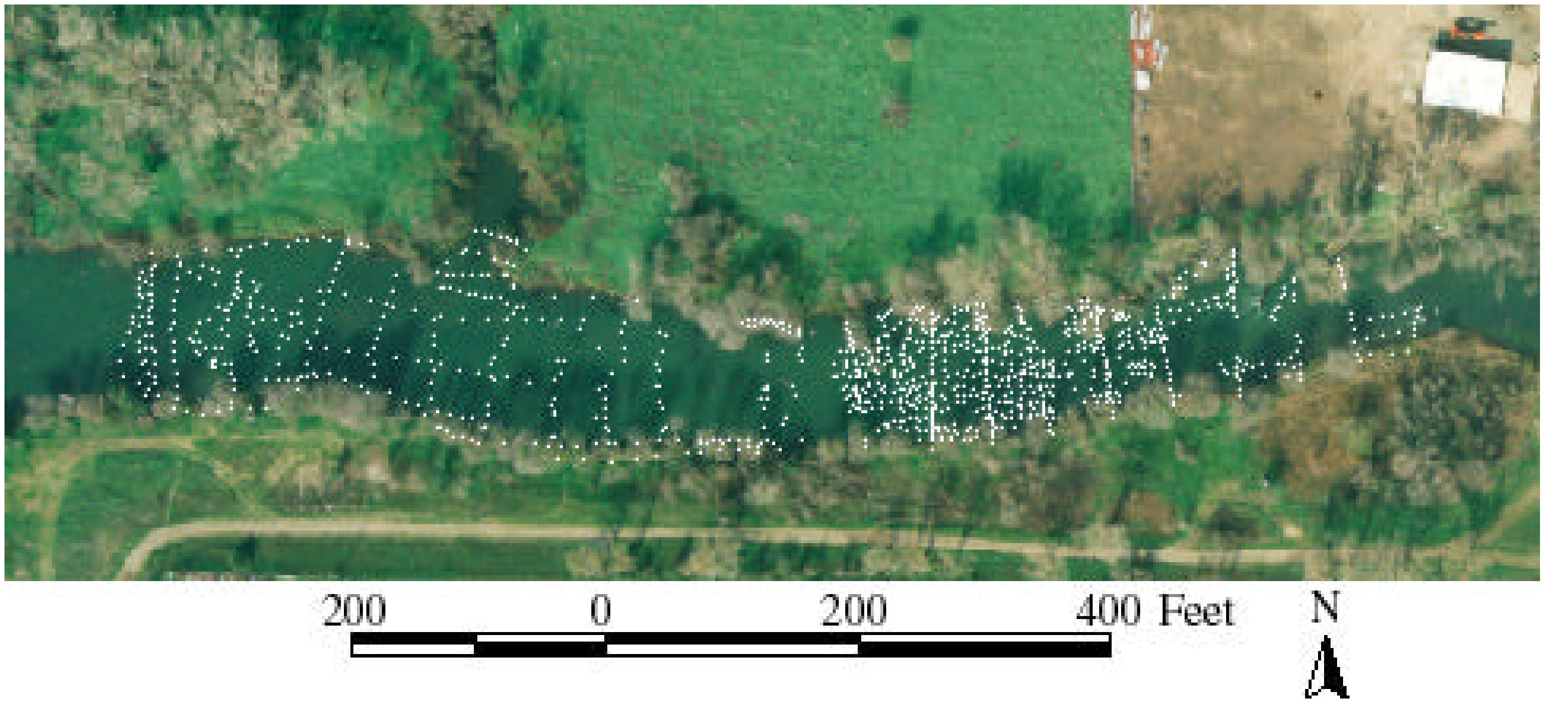
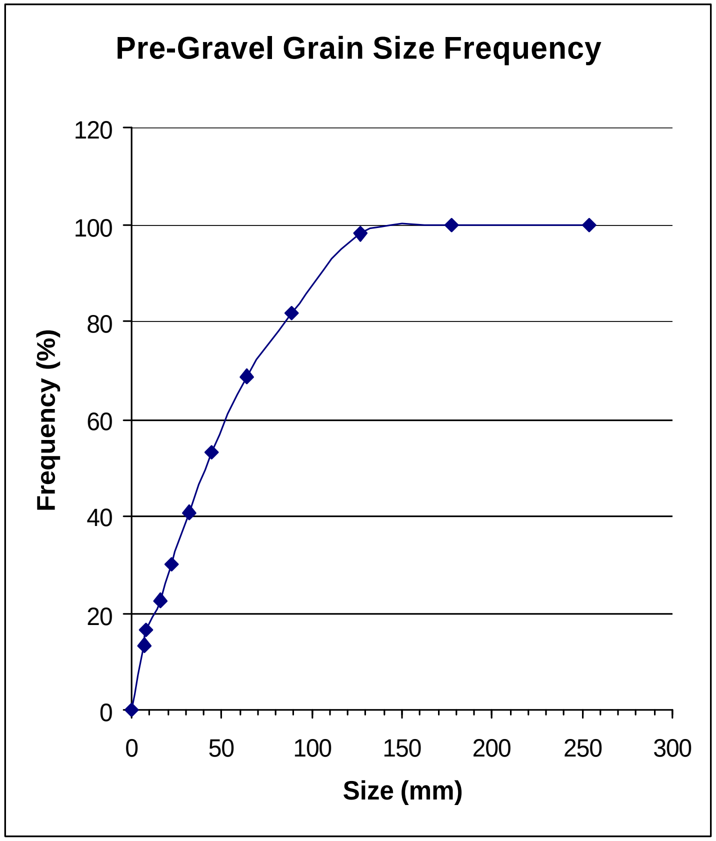


Figure 3. 1995 aerial photo showing 1155 project XYZ survey points, pre- and post-gravel.



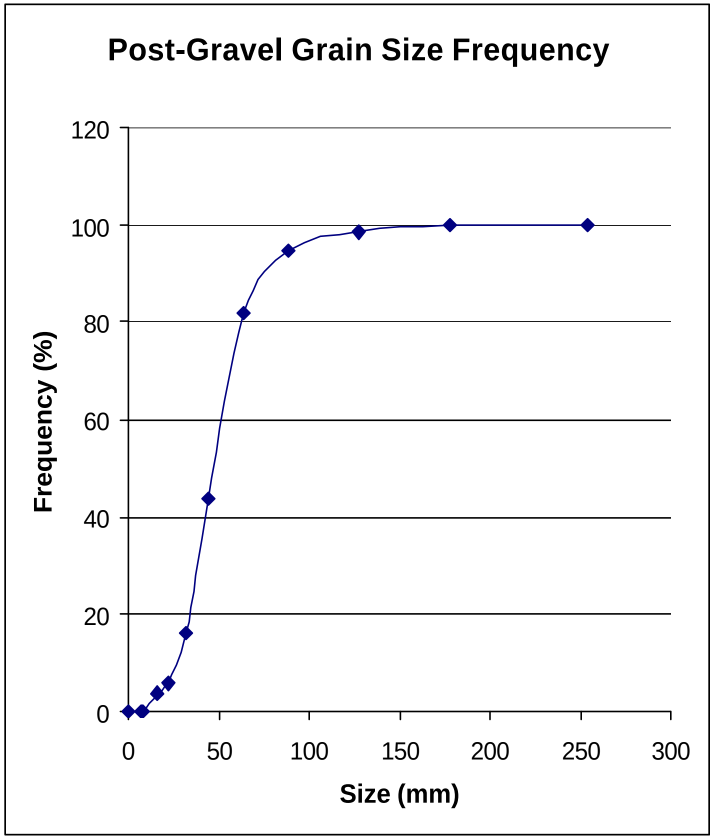


Figure 4. Grain size frequency analysis of pebble count surveys before and after gravel replenishment. Pre-gravel D_{50} = 40 mm or 0.13 ft. Post-gravel D_{50} = 50 mm or 0.18 ft.

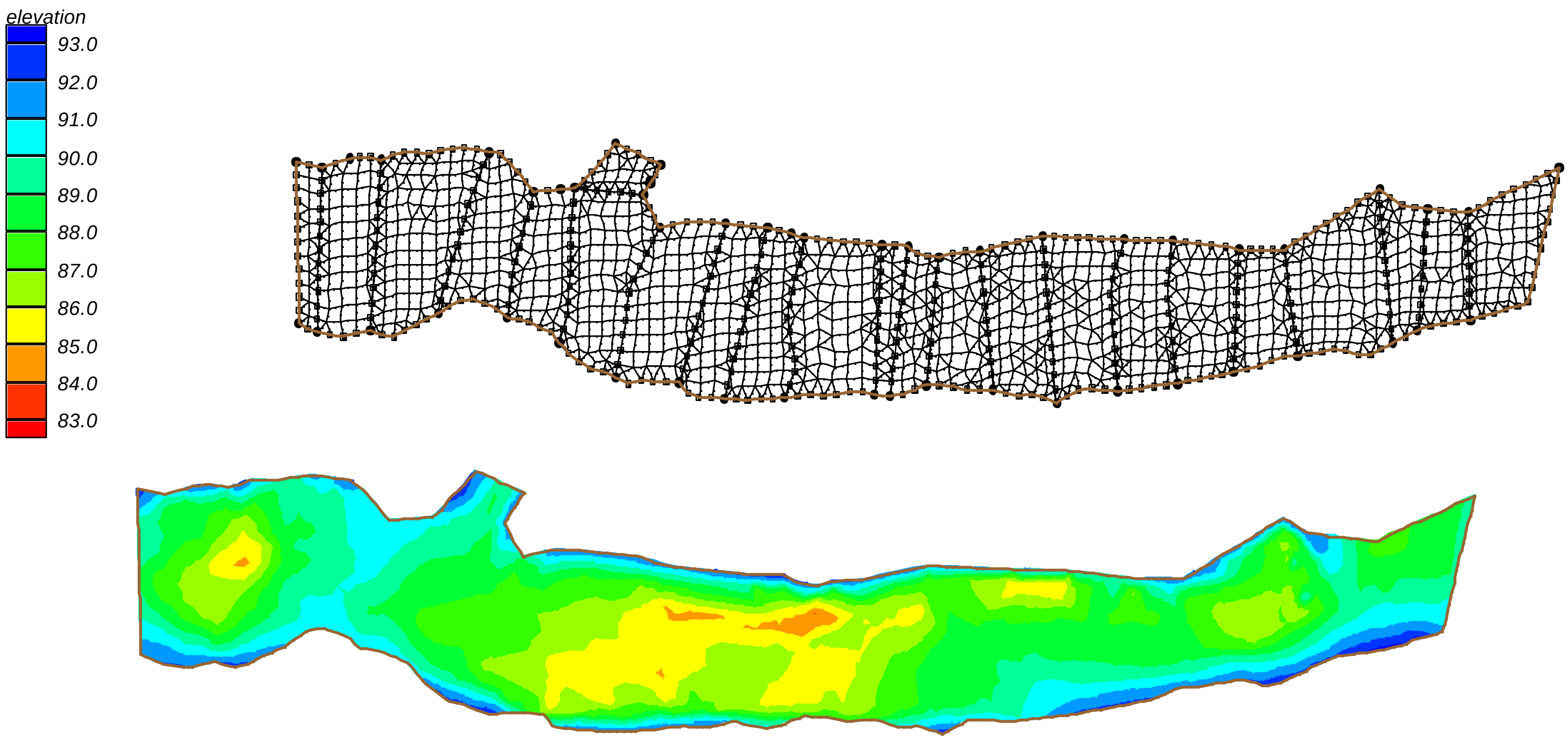


Figure 5. Pre-project mesh and bathymetry. 4888 nodes and 1513 elements interpolated from 807 points.

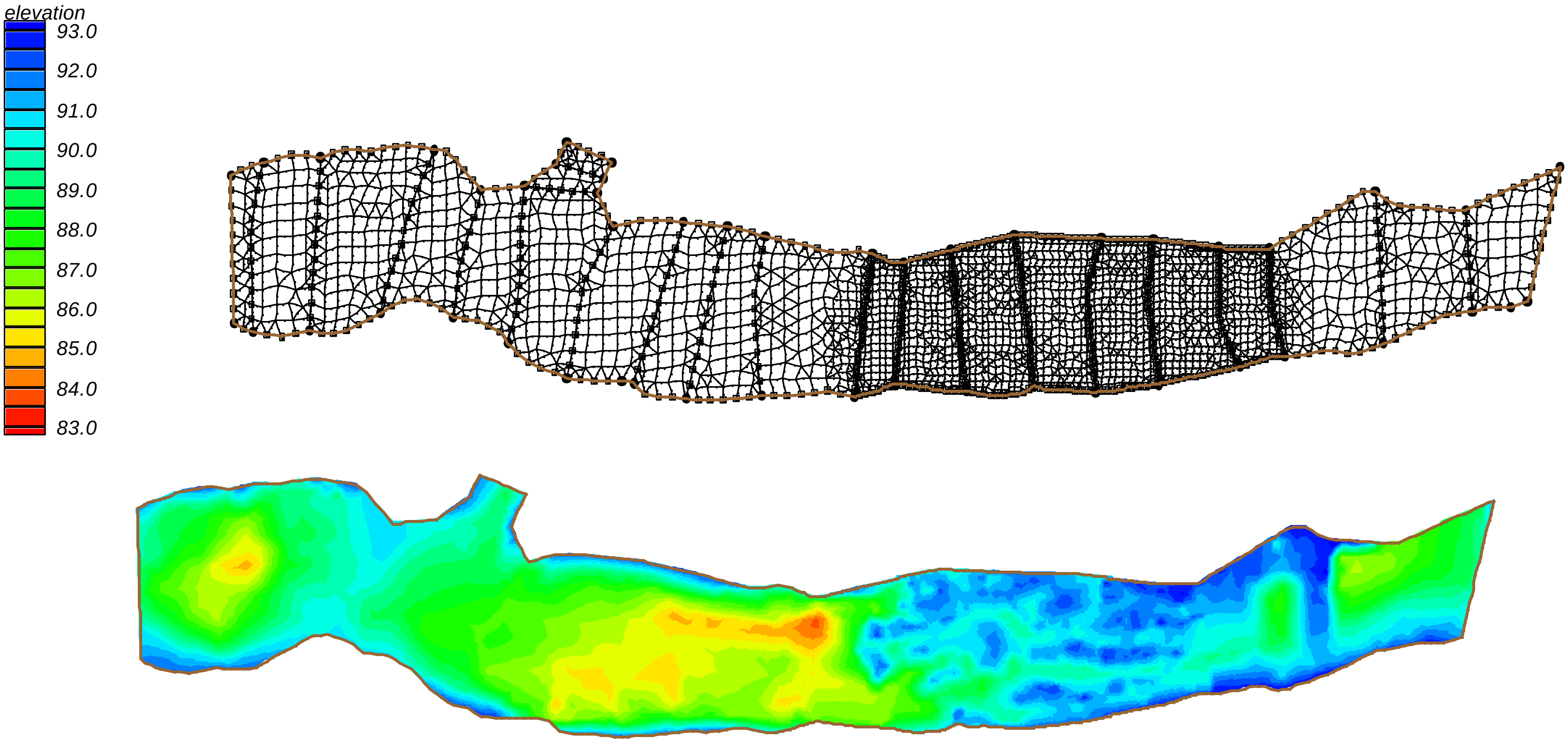


Figure 6. Post-project mesh and bathymetry. 7391 nodes and 2796 elements interpolated from 1155 points.

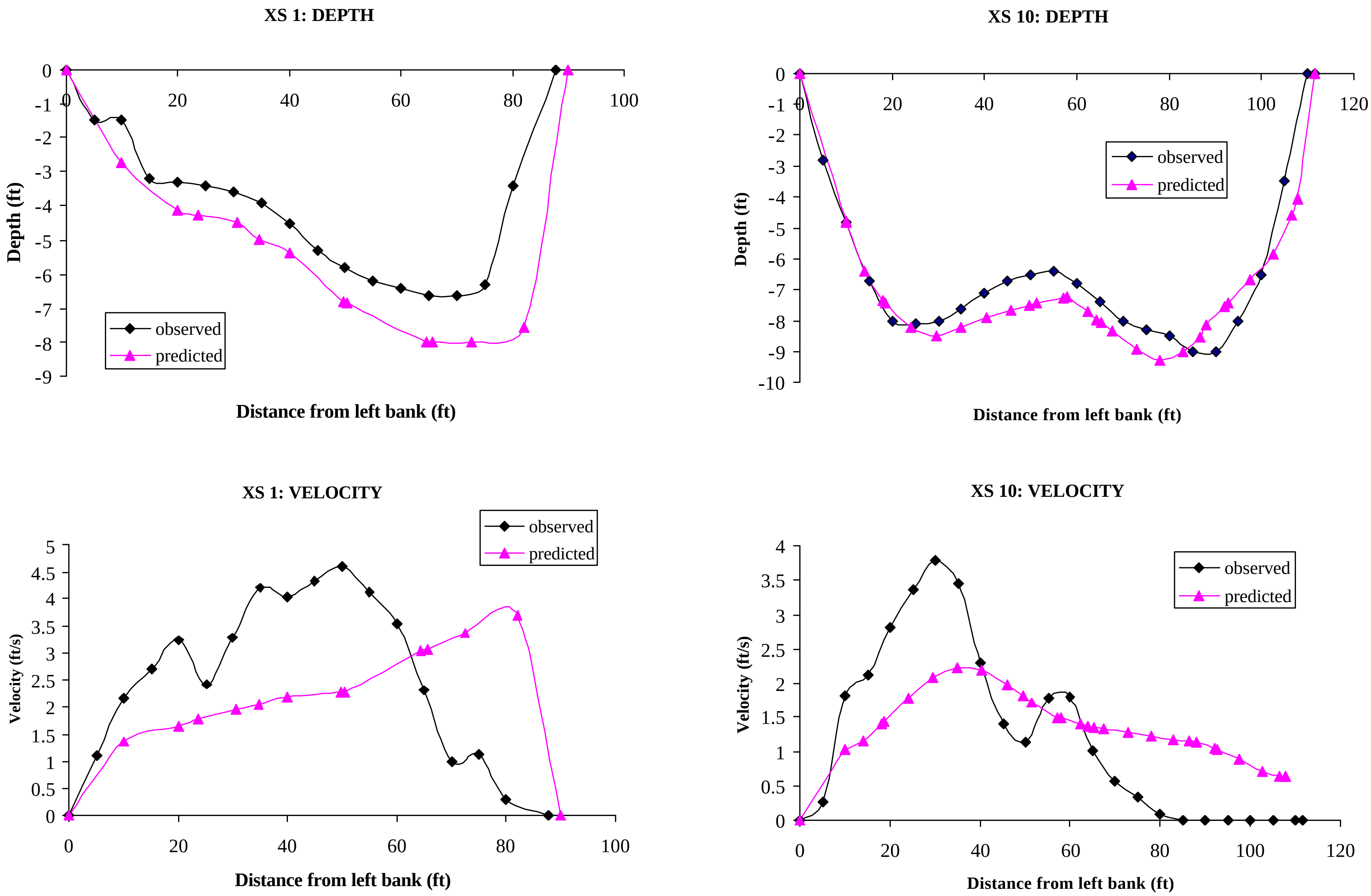


Figure 7. High flow post-gravel observed versus predicted depths and velocities.

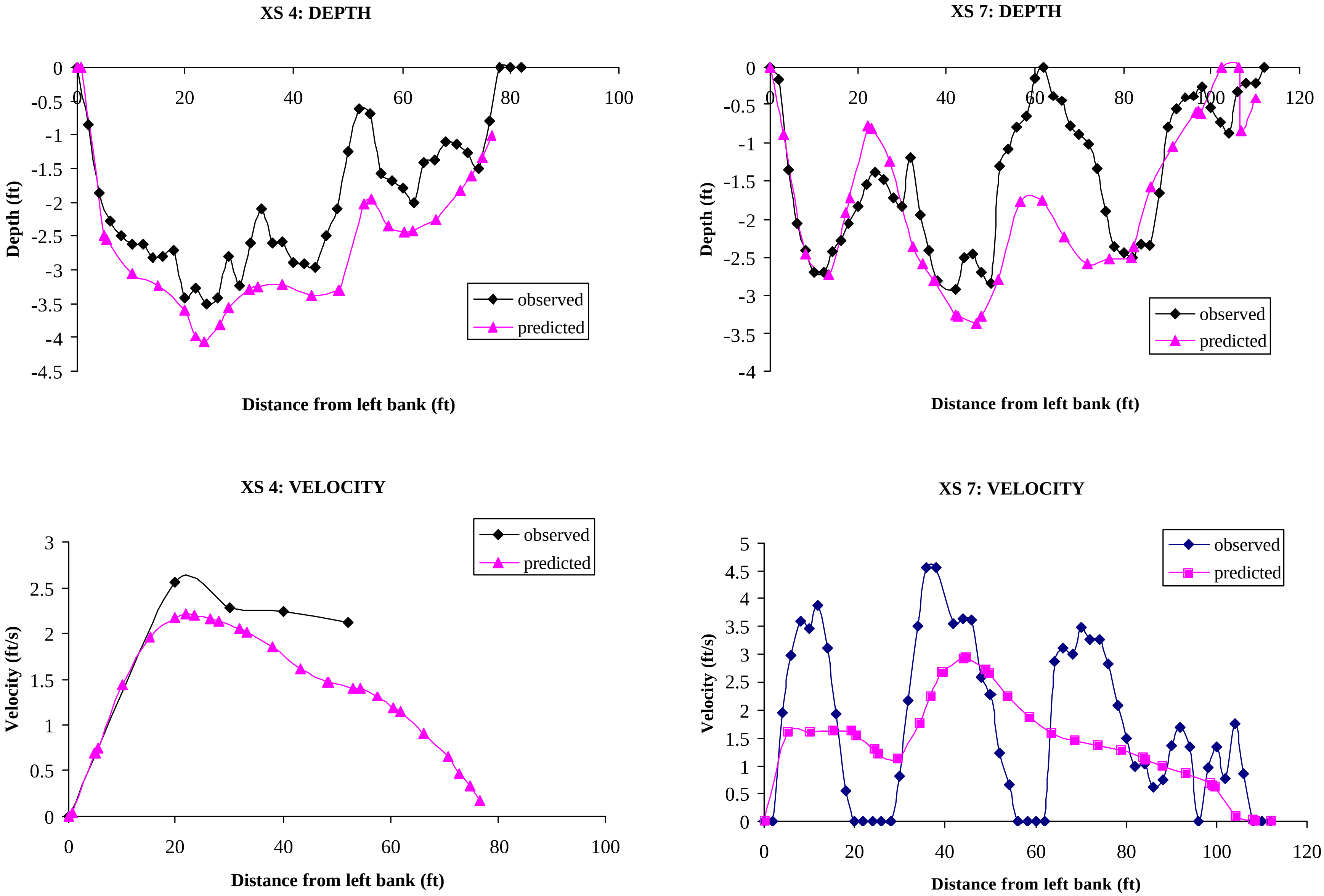


Figure 8. Low flow post-gravel observed versus predicted depths and velocities.

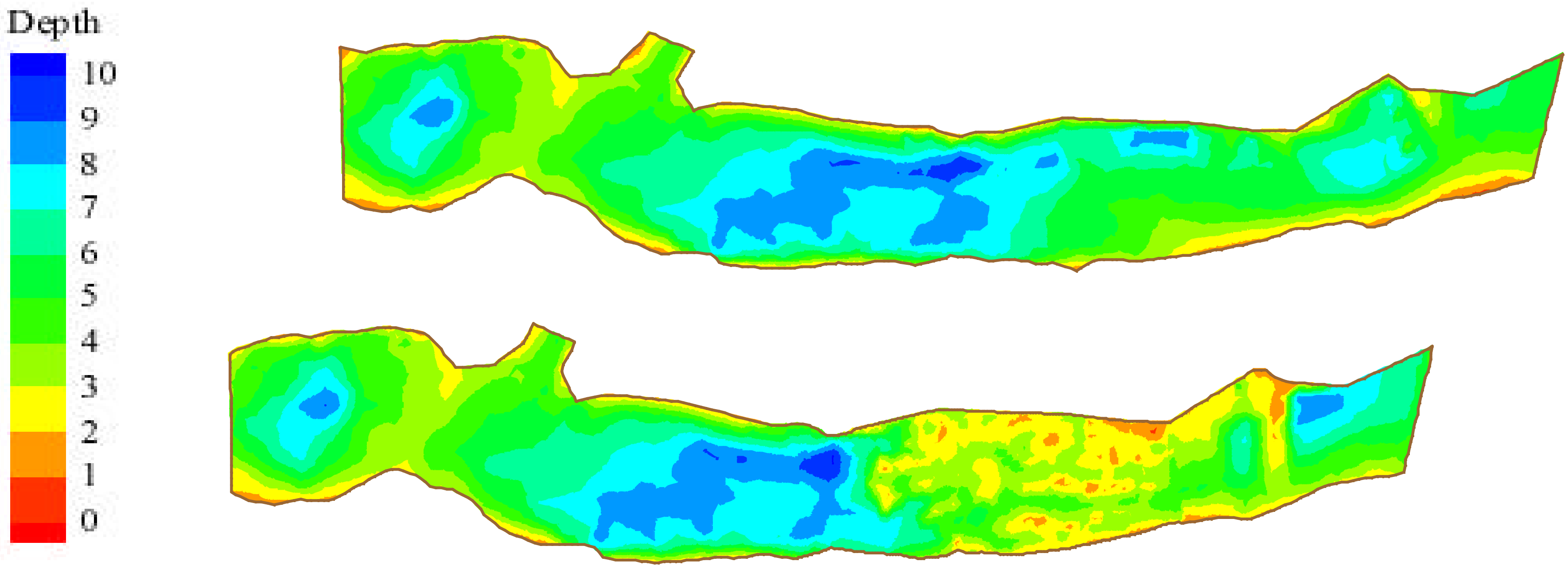


Figure 9. High flow water depths (ft), pre- (above) and post-project (below).

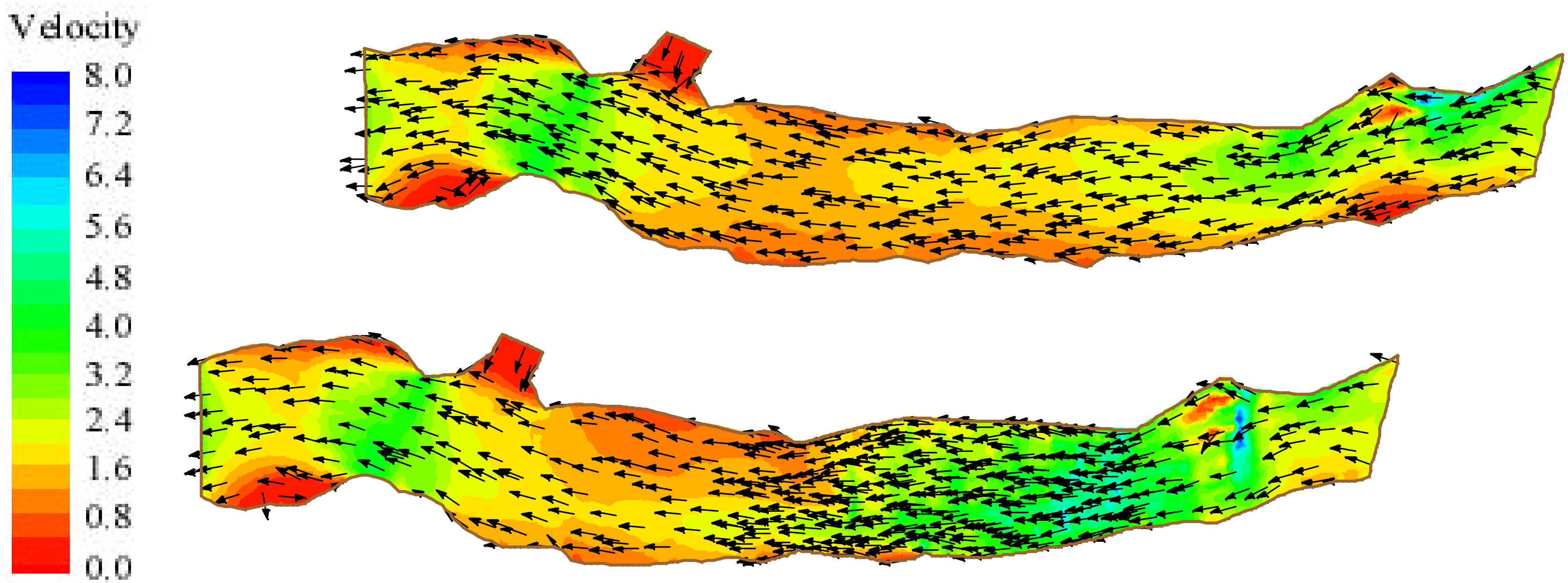


Figure 10. High flow velocities (fps), pre- (above) and post-project (below).

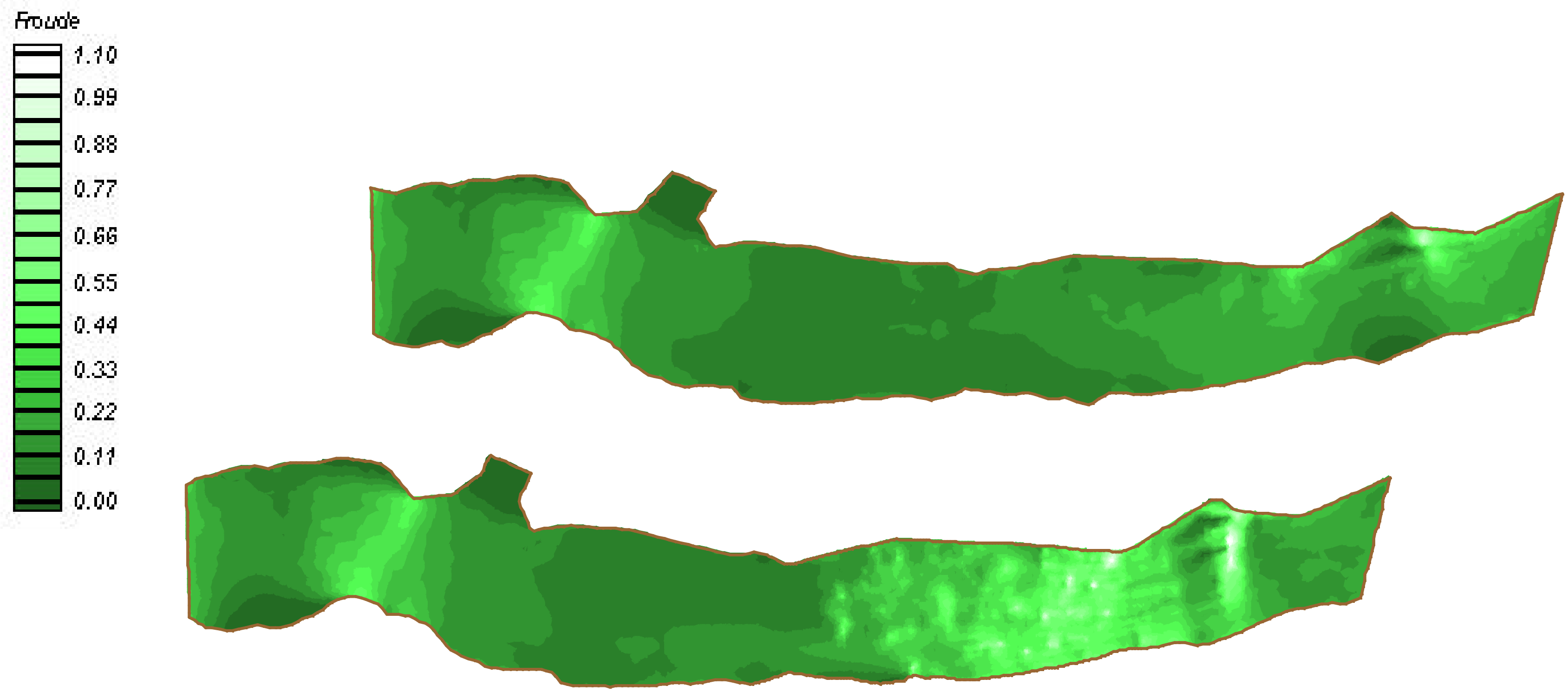


Figure 11. High flow Froude numbers, pre- (above) and post-project (below).
Fr<1 sub-critical, Fr=1 critical, Fr>1 super-critical flows.

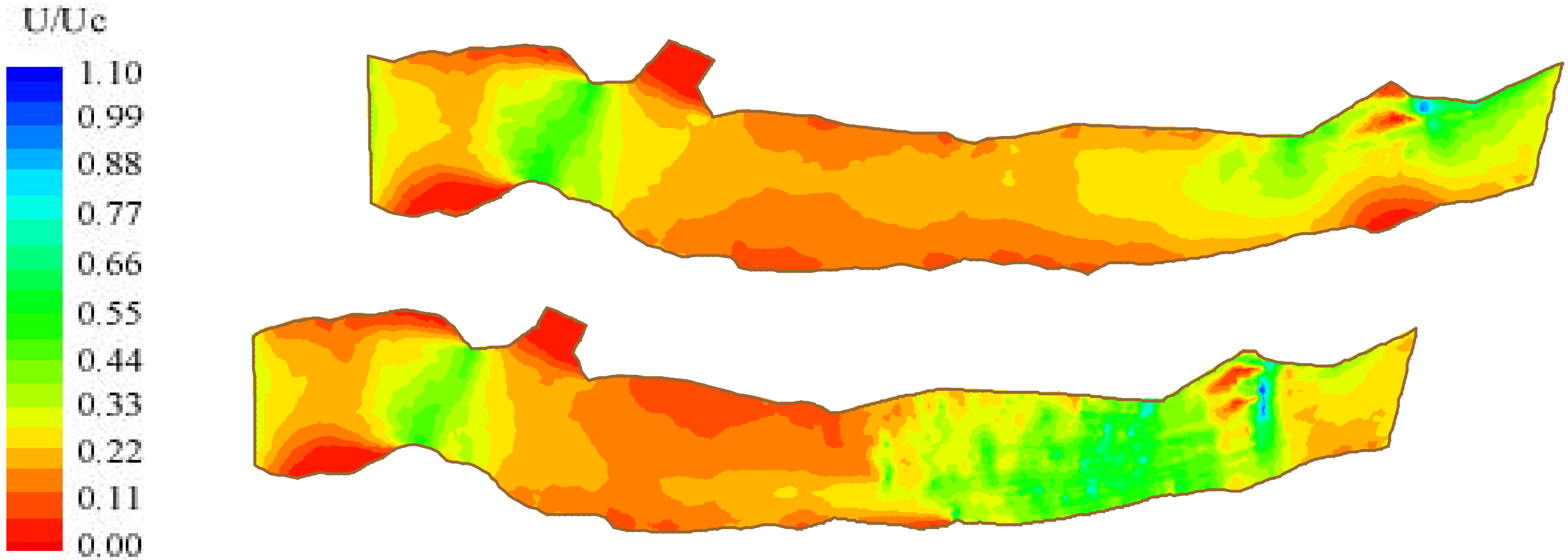


Figure 12. High flow sediment mobility index, pre- (above) and post-project (below).
MI<1 no transport, MI>1, transport predicted.

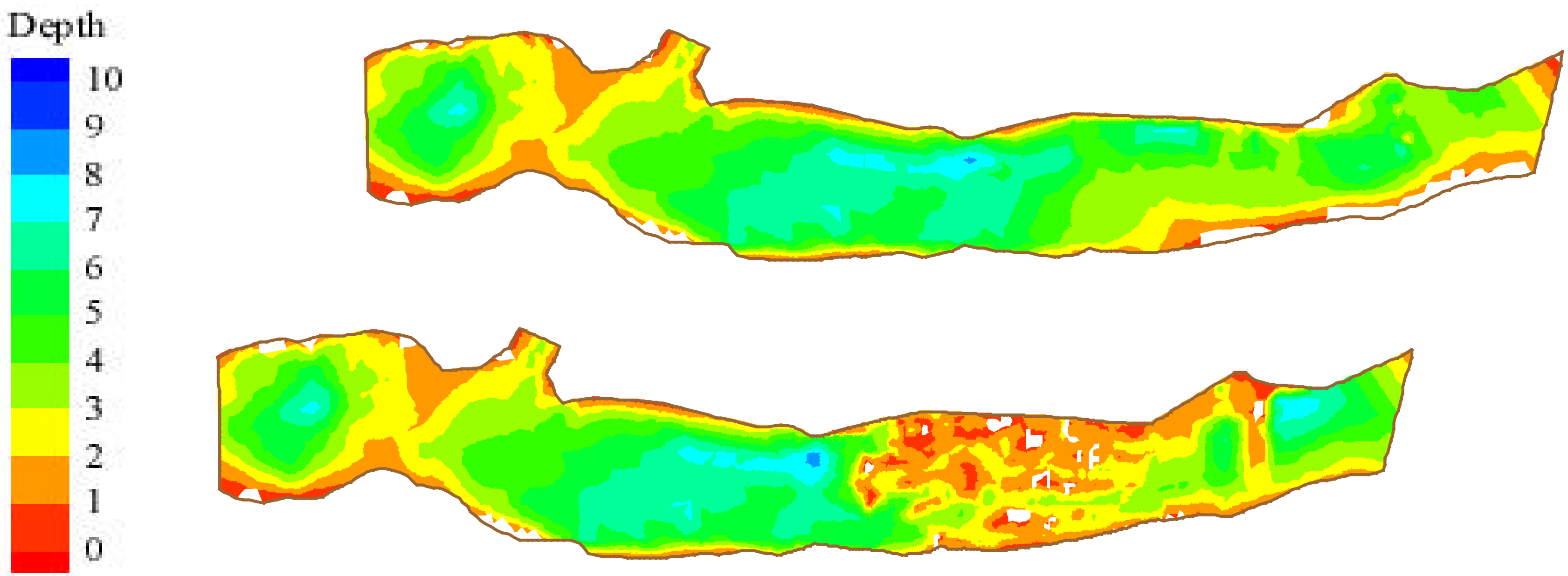


Figure 13. Low flow water depth (ft), pre- (above) and post-project (below).

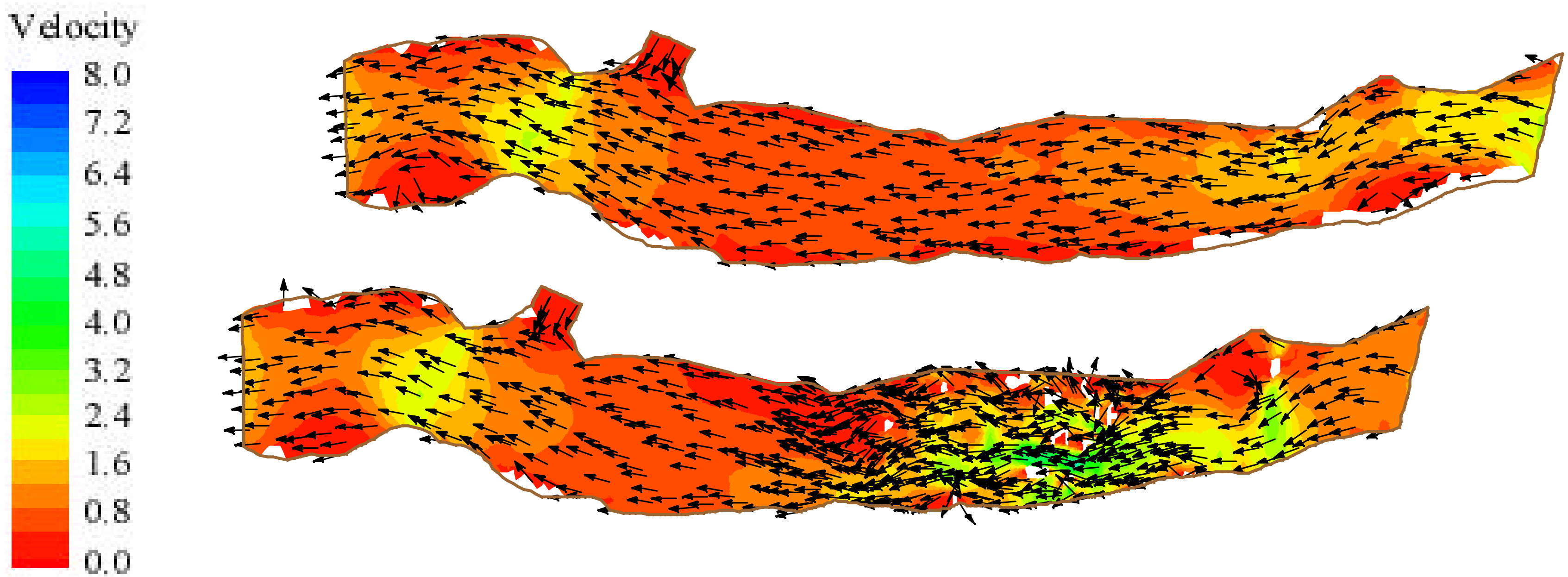


Figure 14. Low flow velocities (fps), pre- (above) and post-project (below).

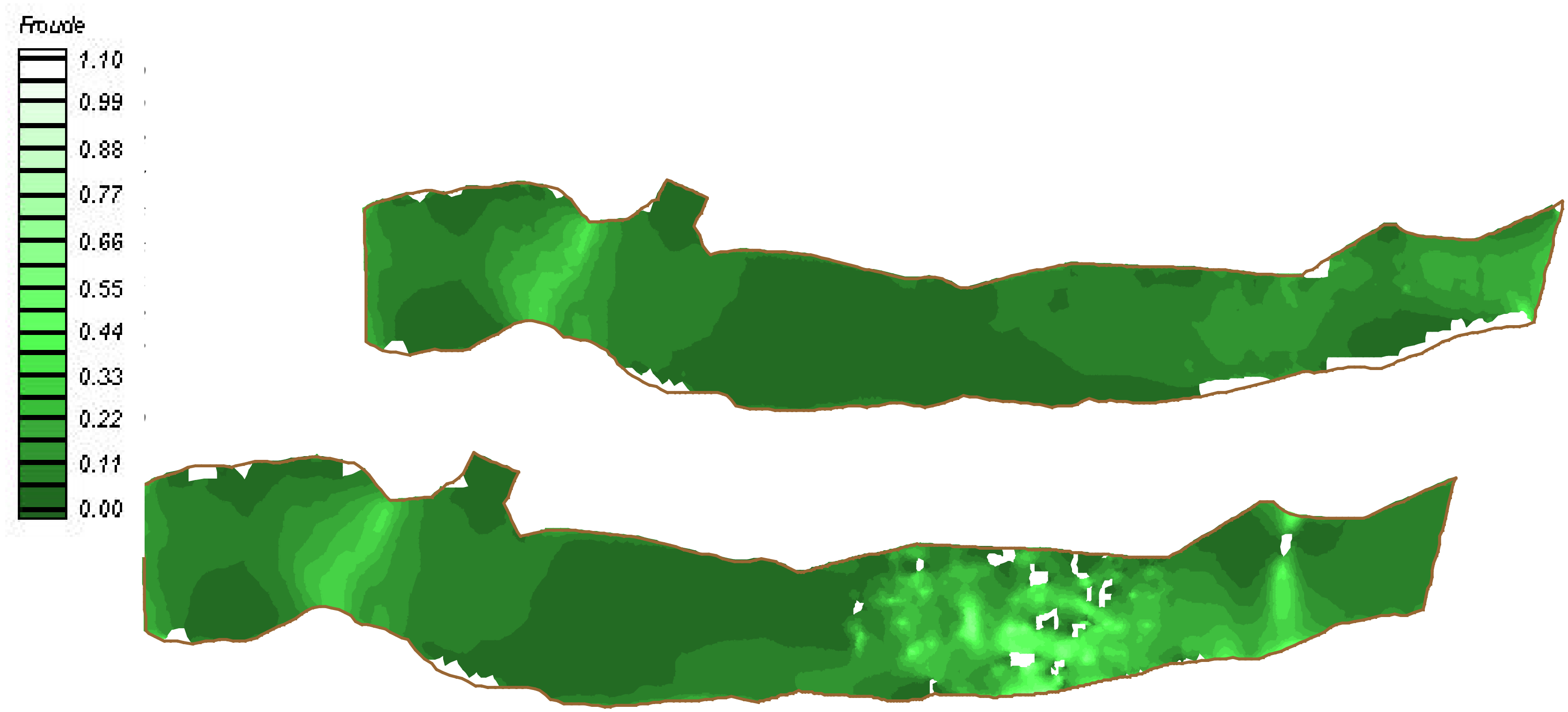


Figure 15. Low flow velocities, pre- (above) and post-project (below).
Fr<1 sub-critical, Fr=1 critical, Fr>1 super-critical flows.

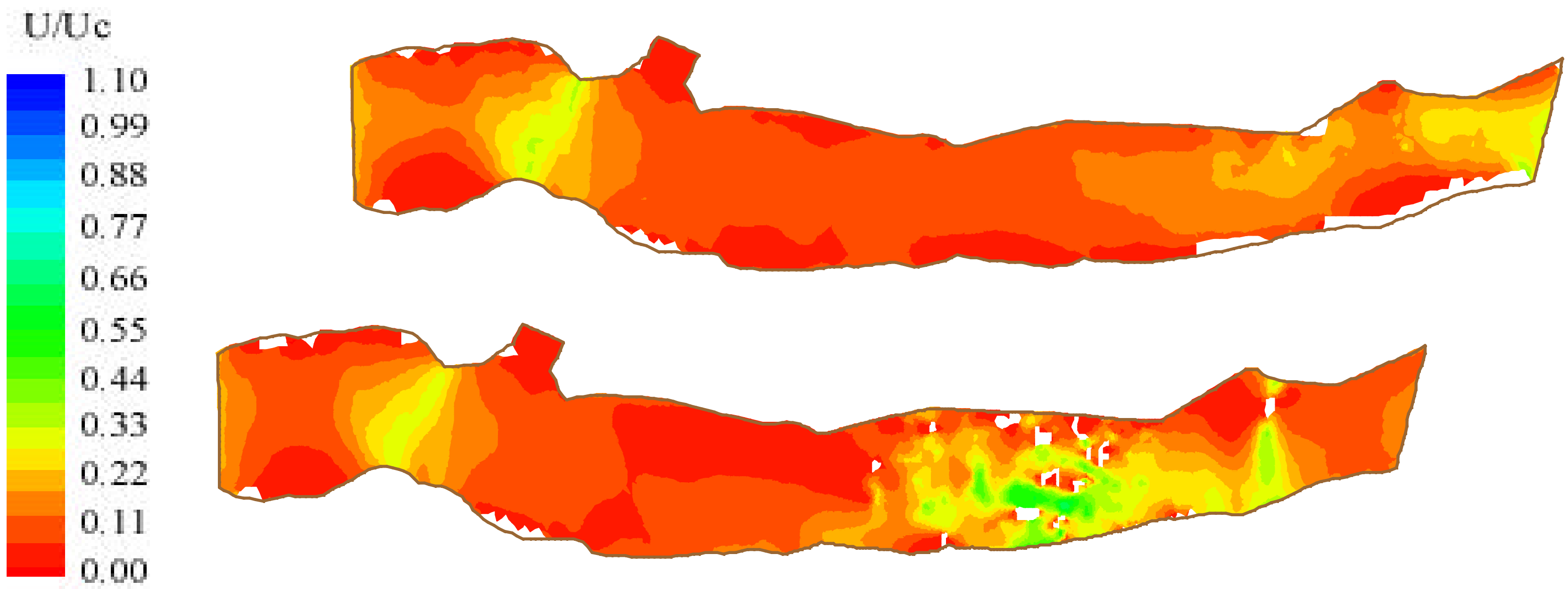
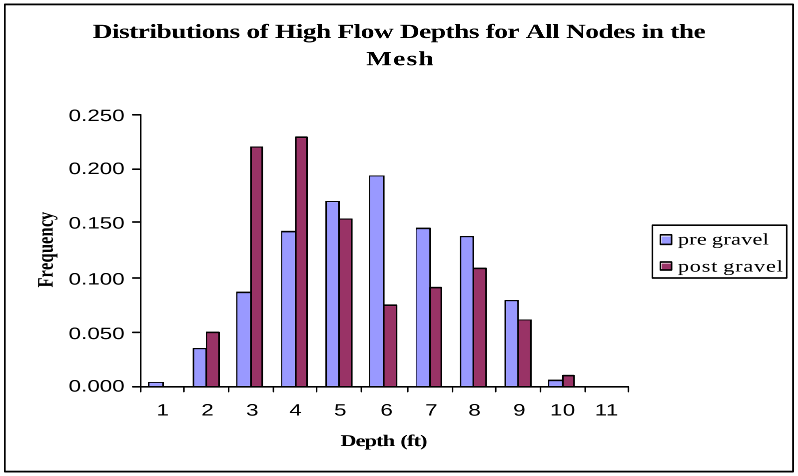


Figure 16. Low flow sediment mobility index, pre- (above) and post-project (below).
MI<1 no transport, MI>1, transport predicted.



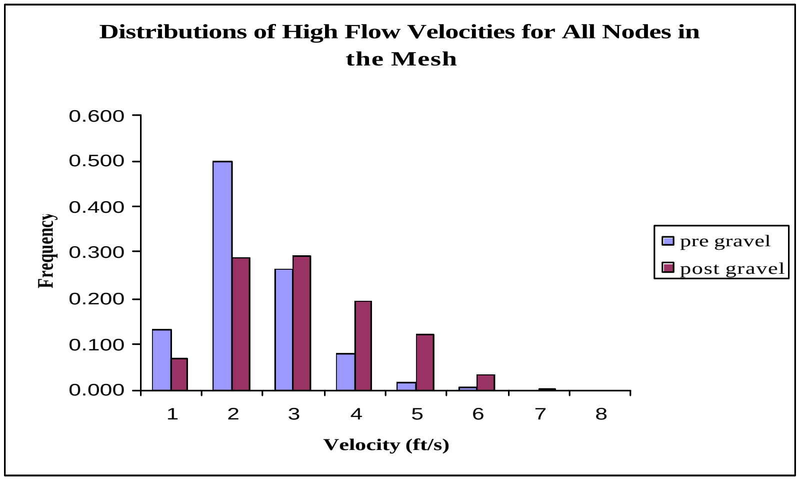
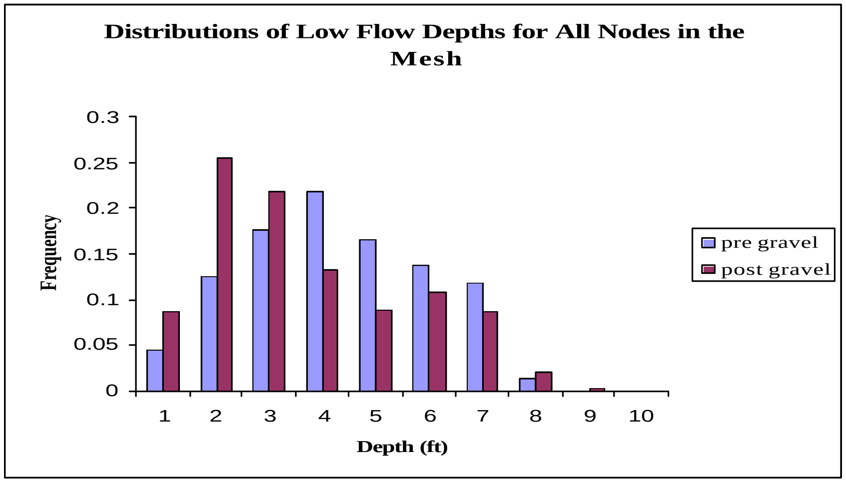


Figure 17. Flow field distributions for all nodes at high flow.



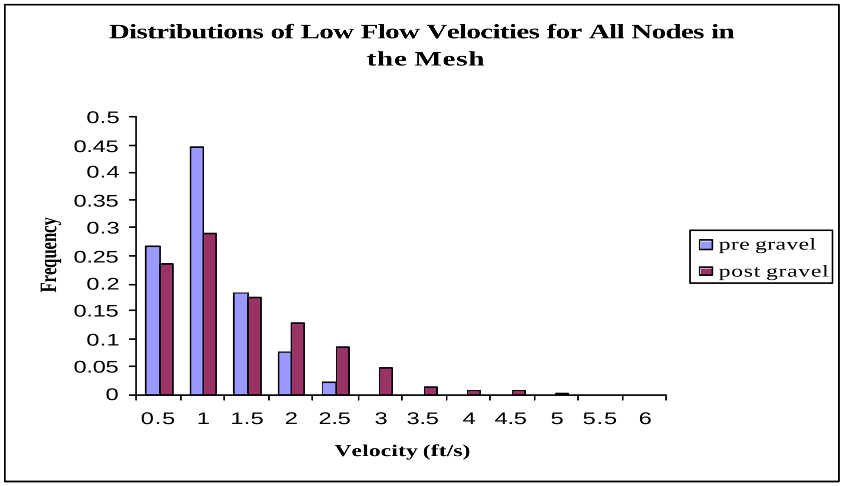


Figure 18. Flow field distributions for all nodes at low flow.